PART I

CHAPTER I

INTRODUCTION

Objects of the Investigations. The duties of the Imperial Geophysical Experimental Survey (I.G.E.S.), as laid down by the Sub-Committee of the Committee of Civil Research[a], and as further determined from time to time by the Geophysical Executive Committee, may be enumerated as follows:

(i) To conduct thorough trials of the principal geophysical methods, and to determine their practical value and limitations under a variety of geological conditions.

(ii) Priority to be given to test areas in which two or more different geophysical methods can be used in combination, since a knowledge of their relative merits is required, and also of the practical advantages to be gained by their conjoint application.

(iii) The work of the Survey to be restricted to areas in which the geophysical results obtained may be checked in a satisfactory manner. In cases where this cannot be done from existing mine or drilling records, arrangements to be made for confirmatory underground exploration, should important geophysical evidence be recorded.

(iv) These trial surveys to be carried out on a normal field scale in specially selected parts of Australia, the choice of areas to be decided, primarily on their suitability for the purposes stated in (i)–(iii) above, but also with due regard to their economic possibilities.

(v) These tests to be carried out by the gravimetric, electrical, and magnetic methods[b] and the scientific information and experience so acquired to be published in full at the close of the Survey.

(vi) Instruction in the use of instruments, and in the application of the methods in the field, to be given to such Australian students and others who may be nominated for this purpose.

With regard to personnel, the recommendations of the Sub-Committee were that the survey party should consist of the following principal members:

(i) The leader, who should have a special knowledge of the electrical method, and who should undertake to report in full detail on the method, apparatus, and every part of the procedure and, at the close of the survey, to prepare the whole for publication.

(ii) One selected Australian physicist to undertake the gravimetric and magnetic surveys. The Department of Scientific and Industrial Research to be asked to provide for his training in England, in consultation with the Science Museum.

(iii) One Australian physicist, who has specialized in electricity, to assist the leader in the electrical surveys.

(iv) Two surveyors and one laboratory assistant.

[a] *Report on Geophysical Surveying*, Published by H.M. Stationery Office, Nov. 1927.
[b] The investigation of seismic methods was initiated at a later date.

It was also recommended that the Survey should be provided with the following equipment at an estimated cost of £4000:

Electrical apparatus.	One magnetometer.
Two torsion balances and accessory equipment.	Survey instruments, etc.
Two motor lorries.	Camp equipment.

Preliminary Organization. The preparatory work in connection with the Survey was carried out at Australia House, London, in February 1928, in close consultation with the Empire Marketing Board, the Department of Scientific and Industrial Research, and the Geological Survey of Great Britain. Instructions were also received from the Geophysical Executive Committee that had recently been formed in Melbourne for the purpose of controlling the activities of the Survey as soon as it commenced operations in Australia. Throughout this preliminary work the advice and guidance of Mr F. L. McDougall, C.M.G., and his staff at Australia House, was indispensable, and to their knowledge of Australian conditions the avoidance of many mistakes is to be attributed.

In the selection of personnel, in accordance with the recommendations of the Sub-Committee, it was apparent that the previous experience of the party would be limited to the electrical methods almost entirely, and that the requisite knowledge of the other branches must perforce be gained after the establishment of the Survey in the field. The appointment of the physicist in charge of gravimetric and magnetic work had already been made, however, in the person of Dr N. B. Lewis of Melbourne and Oxford Universities and, for some months, he had been undergoing his preliminary training in England.

As a result of arrangements which had been made by the Department of Scientific and Industrial Research, Dr Lewis was able to study the Oertling Torsion Balance and the general field procedure of gravimetric surveying under the guidance of the Geological Survey which, at that time, had a gravimetric field party operating in Scotland. Grateful acknowledgment is due to Drs McLintock and Phemister, the two officers of the Geological Survey who were conducting this work, and who also gave valuable advice to the I.G.E.S. on many subsequent occasions. Dr Lewis was also able to spend some time in Cumberland with Messrs Shaw and Lancaster-Jones of the Science Museum, London, who were carrying out a gravimetric survey there over iron-ore deposits. On this occasion he obtained experience with the Gradiometer, a small type of balance that had recently been developed by Messrs Shaw and Lancaster-Jones. As the performance of this instrument was considered to be satisfactory, arrangements were made to secure one for the use of the Imperial Geophysical Experimental Survey. On the advice of the officers of the Geological Survey a large Oertling Torsion Balance and accessory equipment, similar to that employed by the Geological Survey, was also ordered for use in Australia.

In the case of certain of the electrical methods the Survey was in a rather stronger position, since the advantage of several years practical experience in Spain, Portugal, and

South Africa was available, and arrangements could be made to acquire the necessary equipment which, contrary to the cases of the gravimetric and magnetic methods, cannot be purchased in the open market from instrument manufacturers.

Although the officers of the Survey had some previous experience of electrical prospecting operations it should be explained that the position with regard to this branch of applied geophysics was, and still remains, entirely different from that of the gravimetric and magnetic methods, the theory and practice of which have been fully described in published works. The electrical methods have been described in the Report of the Sub-Committee of the Committee of Civil Research[a] as "having been treated by the companies employing them as jealously-guarded secret trade processes," and it must be agreed that there are grounds for this indictment. Although numerous papers on electrical prospecting methods have appeared during the past few years it is most unusual to find information in any of them which can be of the slightest assistance in the design of instruments, or in the use of the methods in the field; in fact, the sincerity of some of these publications is open to considerable doubt. As a result of this difficulty in obtaining information about instruments and procedure many of the electrical investigations carried out by the Survey were necessarily of an experimental character.

In order that the electrical investigations might be commenced in Australia without delay, the appointments of Mr S. H. Shaw, A.R.S.M., B.Sc., and Mr J. C. Ferguson, B.Sc., were approved, both of whom had two years' previous experience in South Africa. At a later stage Dr E. S. Bieler of McGill University, Canada, was appointed Deputy-Director of the Survey, and his previous experience and keen interest in electromagnetic methods of prospecting gave additional support to this section of the work.

In view of the comparative simplicity which attends the use of the magnetic methods and since full details of the procedure are readily available from published works, it was not considered that the services of a specialist were required. This decision was amply justified by subsequent experience in Australia, where it was found that the two vertical variometers of the Schmidt pattern[b], which had been purchased by the Survey, could be used efficiently by any of the technically trained staff.

During these early preparations in London the testing of seismic methods by the Survey was thought to be impracticable, since neither experienced operators nor the necessary equipment could be secured. This branch of geophysical work was entirely in the hands of certain geophysical companies, and not until nearly a year later was it considered possible for the Survey to carry out such investigations. They were then included in the programme of the Survey upon the recommendation of the Australian branch of the Institute of Physics, which drew attention to the fact that, following on their war experiences of seismic methods, the late Professor J. A. Pollock, F.R.S., and Major E. H. Booth of Sydney University had, for some years, been carrying out experiments by an electrical recording system, which is very similar to that now being

[a] *Geophysical Surveying*, H.M. Stationery Office, London, November, 1927.
[b] Made by the Askania Werke of Berlin.

employed in geophysical investigations. Major Booth was available and consented to act as consultant to the Survey in this branch, and on his recommendations the necessary microphones and electromagnetic recording apparatus were obtained. At the same time a standard seismograph of the mechanically recording type was purchased. This instrument[a] had recently been designed by Professor Schweydar of Potsdam and, although a single recording unit only was used by the Survey, it proved of considerable value for purposes of comparison. The field party, which was placed under the charge of Mr R. L. Aston, M.Sc., B.E., conducted field tests over two of the most suitable areas that could be found in New South Wales, and a large amount of valuable information was obtained. A more extensive programme of seismic work was not possible in view of the late date at which the investigations were commenced. Owing to the paucity of published information of a practical character regarding the application of seismic methods to geological problems, the Survey's experience of instruments, methods, and field procedure had to be gained entirely *ab initio*.

In connection with the organization and general policy of the Survey it should be mentioned that several offers of co-operation were received from continental geophysical companies, both directly and through their London representatives, and that in one or two instances the terms that were suggested were most generous. In every case, however, a difficulty existed with regard to the requirement for full publication at the close of the work. Although these companies were agreeable to the publication of results obtained, and even to disclose the details of their methods to authorized members of the Survey, they would not go so far as to concede the right to publish descriptions of the instruments employed, or the methods used in the interpretation of results. This difficulty could not be overcome, since the conditions under which the Survey had been authorized made it essential that the published report should include full accounts of the field procedure, and detailed descriptions of the apparatus employed, without reservations of any kind.

Selection of Areas in Australia. In accordance with the recommendations of the Sub-Committee, the Director of the Survey arrived in Australia several weeks in advance of the other members, in order to make a preliminary examination (without instruments) of areas likely to prove suitable for the purposes of the Survey. After consultation with the Geophysical Executive Committee, and with the State Geologists and the geological adviser to the Federal Government, the several States were visited in turn; every facility being afforded him by the Mines Departments and Geological Surveys. In this manner a large number of promising areas were examined in company with the Government Geologists concerned and, prior to the assembly of the field parties, it was possible, by careful selection, to submit a provisional programme of work for the approval of the Executive Committee.

In spite of the vast area which Australia presented for this purpose of selection, the

[a] Made by the Askania Werke of Berlin.

matter proved to be one of some difficulty; more particularly so in view of those special purposes of the I.G.E.S. which are enumerated on p. 1. Of these several requirements, the most difficult to comply with was that which relates to the confirmation of results; although in a few cases it was possible to select areas in which the mineral deposits, or geological structures, had previously been proved by drilling. Such instances are rare, however, since ore-deposits do not usually remain intact for long after their discovery, and those in course of exploitation are so disturbed, as a rule, that they are quite unsuitable for the testing of geophysical methods. The difficulties attendant on the application of electrical, magnetic, or gravimetric methods in the immediate neighbourhood of mine workings, with their complex systems of electrical cables, iron rails, pipe lines, and underground excavations, will be readily appreciated.

In the majority of the areas which were examined by the electrical methods it was impossible to find standing ore-bodies over which to conduct the special tests in question, and in many instances it was necessary to arrange for systematic surveys of the adjoining country, in the hope that new bodies of mineral might be located. The discovery of mineral was not the primary objective of the I.G.E.S., but in some districts the only way to determine the value of the methods was to see if this could be done. In such cases the most favourable ground was selected in consultation with the Government Geologists, and arrangements were made with the Mines Departments concerned that underground exploration, by drilling or otherwise, would be undertaken in the event of there being any important geophysical results. In many instances there was no alternative to this procedure, since the majority of Australia's base metal mining fields are inactive; the known mines having been worked out and abandoned long ago. In the case of new fields, in which vigorous exploration is in progress, this course might not have been necessary, since newly discovered and only slightly disturbed ore-bodies would be available. It happens, however, that the one or two fields in Australia which answer this description are, on other grounds, not very suitable for geophysical work.

The programme carried out by the Survey is shown below in Table I; the sequence in which the various examinations were made being indicated by numerals, prefaced by the initial letter of the method employed. Thus by E. 10 is meant that the investigation made at Gulgong, in New South Wales, was the tenth carried out by the Electrical Section, and reference to the map of Australia (frontispiece) will show, not only the position of the Gulgong district (E. 10), but also the other geophysical methods that were used there.

The preparation of this programme of work necessitated preliminary visits to a large number of districts, in all parts of Australia, about half of which were rejected, for one reason or another, as unsuitable for the purposes of the Survey. From the experience gained during this process of selection it was apparent that the work of the Survey would mostly take place in the Eastern States, since New South Wales and Victoria presented special problems for gravimetric, seismic, and magnetic investigation, and in Tasmania and Queensland there were favourable opportunities for the application of the electrical methods. The Survey was able to devote considerable attention to the west coast of Tasmania, but, unfortunately, for reasons outside the control of the I.G.E.S., arrangements could not be made for work in Queensland until shortly before the termination of its activities.

TABLE I. *I.G.E.S. Programme of Field Work*

State	Method used			
	Electrical	Gravimetric	Seismic	Magnetic
New South Wales	E. 1 Anembo *sulphide ores*	—	—	—
	E. 2 Captain's Flat *sulphide ores*	—	S. 2 Tallong *surface velocities and underground structure*	—
	E. 3 Leadville *sulphide ores*	—		—
	E. 10 Gulgong *gold deep-leads*	G. 3 Gulgong *gold deep-leads*	S. 1 Gulgong *gold deep-leads*	M. 5 Gulgong *gold sub-basaltic deep-leads*
Victoria	E. 4 Cooper's Creek *copper sulphides*	—	—	M. 2 Cooper's Creek *basic dyke*
	E. 7a Mallee *water horizons*	G. 1 Gelliondale *brown coal*	—	M. 1 Gelliondale *brown coal*
	E. 9 Laverton *brown coal*	G. 2 Lakes Entrance *oil structures*	—	—
Tasmania	E. 5 Zeehan *silver-lead sulphides*	—	—	—
	E. 6 Zeehan *copper-nickel sulphides*	—	—	—
	E. 6a Renison Bell *stanniferous pyrrhotite*	—	—	M. 3 Renison Bell *stanniferous pyrrhotite*
South Australia	E. 8a Moonta and Wallaroo *copper sulphides*	—	—	M. 4 Kadina *magnetic body*
	E. 11 Port Lincoln *graphite*	—	—	—
Western Australia	E. 7 Northampton *lead sulphide*	—	—	—
Queensland	E. 8 Chillagoe *copper-lead sulphides*	—	—	M. 6 Chillagoe *magnetite bodies*

Organization of Field Work. The original conception of the Survey was that of a single mobile unit provided with gravimetric, electrical, and magnetic instruments, together with the personnel required for their use. The party was to be supplied with camp equipment and motor transport, so that it could move freely from one district to another, applying suitable combinations of geophysical methods to the particular problems that had to be dealt with. In theory such an arrangement has much to commend it, but within a week or so of arrival in Australia it was agreed that this was entirely impracticable, for the following reasons:

Firstly, the gravimetric and the electrical were the two principal methods to be employed, and since their practical applications are so different, it was not surprising that no areas could be found in which they might be used in combination. The necessity for separating the two methods was apparent from the start, since to keep both personnels and equipments together in a district suitable only to one of them was out of the question. It was also realized that at any time, should the occasion arise, the two parties could be brought together again for as long as might prove necessary.

Secondly, it was apparent that the field of operations was the Australian continent as a whole, and that great distances had to be covered by rail in moving between the different States. These moves would take place at frequent intervals and, for reasons of efficiency and economy, it would be necessary that living accommodation and transport should be obtained locally. In most instances the areas selected for work were situated on established mining fields, and within a mile or two of house accommodation of some kind. Actually, in having nothing but instruments to transport from State to State, the Survey parties were far more mobile than would have been the case had they been encumbered with camp equipment and road transport of their own.

At a somewhat later stage the formation of a seismic party, and the sub-division of the electrical section into two independent units, resulted in a still greater decentralization of the work, and the Director and Deputy Director were then occupied in a continuous round of visits, spending a week or two at a time with each field party.

The administration of the field parties was carried out from the offices of the Council for Scientific and Industrial Research in Melbourne, where the Field Secretary to the Survey was occupied with supply and transport arrangements, cost and store keeping, and a variety of other general office work.

General Remarks. From Table I it will be observed that the number of areas examined electrically is far in excess of those dealt with by the gravimetric method. This is largely due to the greater speed of working which is possible with the former system, but also to the fact that the mining fields of Australia offered a greater number of opportunities for electrical investigations; so much so in fact that it was decided, early in 1929, to subdivide the electrical section into two independent field parties, so that a more extensive programme might be undertaken. Gravimetric surveying, on the other hand, is relatively a slow procedure and only occasionally do opportunities arise for employing it on metalliferous mining fields. Unquestionably it is more suited to investigations of geological structure, such as may arise in coal and oil fields, than to the direct location of ore-bodies, although opportunities for work of the latter kind sometimes do occur. Nevertheless, the comparatively small programme of work completed by the gravimetric section is to be attributed, very largely, to the serious instrumental difficulties that were experienced, rather than to the slowness of the method or absence of suitable problems. These instrumental troubles became so serious in January, 1929, that the party had to be withdrawn from the field altogether and was unable to resume until the following May.

It has already been explained that the seismic investigations were initiated at a late period in the life of the Survey, and that operations in the field were not commenced until January, 1929. The work of the section, although conducted on a field scale and with a view to structural investigations, was largely of an experimental character.

Throughout the period of the Survey the magnetic work was considered as subsidiary to the gravimetric and electrical investigations, the instruments being used by these sections whenever it was considered that additional information might be gained by doing so. In two instances the magnetic results proved to be of such importance that the method assumed priority over the other systems. In these cases observers were appointed for the purpose of making detailed magnetic surveys.

Although the investigations made by the I.G.E.S. were mostly carried out on long-established mining fields in which prospecting operations by the more usual methods had often been very thorough, a satisfactory proportion of positive results was obtained. Out of eighteen districts which were visited by the Survey, fifteen were examined for the purpose of testing various geophysical methods over mineral deposits, or in order to locate particular structures with which mineral might be expected to occur. Two were selected for electrical investigations in connection with underground water problems, and one for the determination of velocities by the seismic method. In eleven of these districts satisfactory results were obtained by one or more of the methods employed, and in several instances important discoveries of mineral were made. In the remaining cases the surveys were either unsuccessful or gave indications that were not up to expectations. It should be mentioned, however, that in several of the districts which were visited the chances of success were known to be rather remote. For example, saline underground water is prevalent in many of the Australian mining fields, and is so adverse a factor in the cases of the electrical methods that special investigations of the problem were carried out by the Survey in several of the affected areas. The possibility should also be borne in mind that, in some cases, the failure to locate mineral might well have been due to the fact that no mineral was present in the ground that was examined.

CHAPTER II

ELECTRICAL METHODS

SECTION I. PRINCIPLES AND APPLICATIONS

Introduction. There are numerous geo-electrical methods of prospecting, differing one from another in various respects. In some cases the differences are of a fundamental character, but in many they are notable merely as minor variations in the manner of application and in the design of apparatus. Five representative systems have been investigated in Australia by the I.G.E.S., the general principles of which are explained in the following sections of this chapter, and are followed by an account of practical results obtained in the field. In Part II, the theoretical details are discussed at greater length and full descriptions are given of the instruments employed.

Whether applied to the discovery of mineral deposits, or to the elucidation of geological structures, the successful operation of these methods is primarily dependent upon the existence of well-marked differences in electrical conductivity, either between ore-bodies and the rocks enclosing them, or between contiguous geological formations when structural problems are to be investigated. Their practical applications are largely concerned with the search for metalliferous deposits, since those ore-minerals which possess a metallic lustre, such as the sulphides of copper, iron, and lead, are with few exceptions good conductors of electricity which, in relation to the country rocks enclosing them, may afford conductivity ratios ranging from several thousands to several millions to one. More recently, however, it has become evident that electrical methods have a much wider range of practical application, since they are now being employed with considerable effect in a variety of geological investigations[a]. For example, there is ample evidence to show that, under favourable conditions, it is possible to make satisfactory determinations of the depth to the water table, or to bed-rock in country covered by recent and unconsolidated formations.

Resistance Values of Rocks and Minerals. From what has been said above it will be understood that relative electrical conductivities are the primary considerations in determining the practicability of these geo-electrical investigations. In practice, it is usual, and more convenient, to express the conductive properties of rocks and minerals in the form of the reciprocals of their specific conductivities. These values are known as the specific resistances, or resistivities, of the materials in question and are given in ohm cm.[b]. Resistivity tables appear in most of those geophysical publications that deal with the electrical methods, but they are often more misleading than useful, since they are mostly compiled from determinations made in the laboratory on specially prepared rock specimens which, owing to loss of moisture and to other factors, are in no way representative of the naturally occurring formations from which they have been taken.

[a] The value of electrical methods in this connection was indicated by C. Schlumberger as far back as 1920, see *Étude sur la Prospection Électrique du Sous-Sol*, Gauthiers Villars et Cie, Paris, 1920.

[b] An ohm cm. is the resistivity of a one centimetre cube, the resistance of which to a current passing between two opposite faces is one ohm.

That this is the case has been established by several workers[a] who have shown quite conclusively that the electrical resistivity of any normal rock, as it occurs undisturbed in nature, is determined almost entirely by the moisture it holds, both on account of its porosity and as a result of the numerous fissures and joint planes which traverse it. At depths of a few hundred feet from the surface, with which most electrical prospecting operations are concerned, this moisture content is the predominant factor, and country rocks which may give resistivity values of the order of 10^8 to 10^{11} ohm cm. when examined in a dry state in the laboratory will rarely show more than a few hundred thousand ohm cm. when tested *in situ*.

It is apparent, therefore, that in rock formations the passage of current is largely electrolytic in character, whereas in the case of ore-minerals of good conductivity the conditions are similar to those that obtain in metallic conductors. Nevertheless, even in the latter cases, electrolytic conductivity may play a very important part.

The values given in Table II will serve as a general indication of the order of resistivities of rocks and minerals met in practice. In the case of rocks these are mean values for large volumes of the undisturbed formations as they occur in place within a few hundred feet of the surface[b], but in areas where the underground waters are free from any abnormal content of soluble salts.

In determining the suitability of an area for electrical prospecting operations, one of the first points to be investigated is that of the resistivity of the country rocks in which the mineral deposits are likely to be found. For reasons given above, these tests must be carried out upon the ground itself and not upon specimens, however carefully the latter may have been collected. The resistivity methods described in Section 2 of this chapter are recommended for this purpose, since they are simple in application and give a more accurate record of the mean value of the ground resistivity, and of the change in this value with increasing depth from the surface, than is possible by any other method. In the case of the mineral itself it is often impracticable to make *in situ* tests. Resistivity determinations should then be made upon ore-samples considered to be characteristic of the district to be surveyed.

Particular importance is to be attached to the resistivities of the overburden and surface soils, as several of the electrical methods may be at a serious disadvantage if these are low (i.e. less than 500 ohm cm.). In some cases, where the overburden is thick and of low resistivity, the screening effect will be so great that the prospects of success will not be sufficiently good to warrant an electrical survey. In other instances, where the ground resistivities are found to be on the low side, it may be possible to take special steps to minimise the adverse effects; for example, by using a direct current method, or frequencies below 100 cycles per second, in place of the higher frequencies of 500–60,000 cycles that are more commonly employed, and which result in a serious degree of absorption by highly conducting strata.

[a] *Geophysical Prospecting 1929*, pp. 62 and 221–4, A.I.M.E., New York, 1929.
[b] Determinations made on surface exposures and involving relatively small volumes of rock may yield values several times greater than those given in Table II.